Organic complementary-like inverters employing methanofullerene-based ambipolar field-effect transistors

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We demonstrate a complementary-like inverter comprised of two identical ambipolar field-effect transistors based on the solution processable methanofullerene [6,6]-phenyl-C61-butyric acid methyl ester (PCBM). The transistors are capable of operating in both the p- and n-channel regimes depending upon the bias conditions. However, in the p-channel regime transistor operation is severely contact limited. We attribute this to the presence of a large injection barrier for holes at the Au/PCBM interface. Despite this barrier the inverter operates in both the first and third quadrant of the voltage output versus voltage input plot exhibiting a maximum gain in the order of 20. Since the inverter represents the basic building block of most logic circuits we anticipate that other complementary-like circuits can be realized by this approach. © 2004 American Institute of Physics.

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Organic field-effect transistors (OFETs) are currently the focus of intense research efforts in numerous academic and industrial research laboratories around the world. Over the past decade OFETs have emerged as promising candidates for electronic device applications requiring low cost and large area coverage, mechanical flexibility, and low temperature processing. Several groups have demonstrated OFET-based circuits with performances sufficient for practical applications. Few examples of such applications include switching devices for flat panel displays and integrated circuits. To date the largest organic-based electronic circuit reported is the standard logic based 32-stage shift register of order 10^6 . Here, we demonstrate that OFETs based on solution processable methanofullerene derivative [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) exhibit ambipolar transport characteristics even when a high work function metal (Au) is employed as the source and drain electrodes. We found that the carrier mobilities in this particular methanofullerene are in the order of 10^{-5} cm^2/Vs for electrons and 8 \times 10^{-3} cm^2/Vs for holes with on-off current ratios \approx 10^6. Here, we demonstrate that PCBM based ambipolar OFETs can be used for fabrication of CMOS-like logic inverters with good operating characteristics.

Field-effect transistors were made using heavily doped p-type Si wafers as the common gate electrode with a 200 nm thermally oxidized SiO2 layer as the gate dielectric. Using conventional photolithography, gold source and drain electrodes were defined in a bottom contact configuration with channel width of 1000 \mu m and lengths in the range 0-6951/2004/85(18)/4205/3/$22.00 © 2004 American Institute of Physics
0.75–40 μm. A 10 nm layer of titanium was used acting as an adhesion layer for the gold on SiO₂. The SiO₂ layer was treated with the primer hexamethyldisilazane prior to semiconductor deposition in order to passivate its surface. The drain electrode was contained within a circular source conductor deposition in order to passivate its surface. The device currents were identical and equal to 10⁻³ cm²/V s at V_G=−20 V. The drain current in (b) observed for V_D in the range |V_D|>|V_G|>0 V is due to electron contribution (see Refs. 7, 10, and 14).

FIG. 1. Room temperature transfer characteristics for a PCBM based OFET with a characteristic channel length and width of 20 and 1000 μm, respectively. (a) Transistor operation in electron accumulation at V_D=+20 V. Inset shows the schematic diagram of the top view of the ring-type transistor geometry used and the molecular structure of PCBM. (b) Transistor operation in hole accumulation at V_D=−20 V. The drain current in (b) was observed for V_D in the range |V_D|>|V_G|>0 V is due to electron contribution (see Refs. 7, 10, and 14).

In order to obtain some insight in the contact effects present in our devices we have calculated the contact resistance R_C (drain+source contacts) using the transmission line method described elsewhere.¹⁸ Figure 2(a) shows the derived values of R_C as a function of gate voltage in n- as well as p-channel operating regime. It is evident that for both channels R_C is strongly dependent on V_G. The contact resistance for the p channel, however, is several orders of magnitude higher than the values measured for the n channel, implying a severely contact limited device operation. Such high resistance is consistent with the presence of a rather large injection barrier for holes¹⁴ and can be better understood in terms of the energy level diagram shown in Fig. 2(b). In this diagram the energy difference between the Fermi level of Au and the energy levels of PCBM, before and after contact are shown. For simplicity, here the energy levels are drawn flat but in reality band bending occurs upon contact, as well as upon application of a gate bias. From the band offsets (before contact), potential barriers Φ_D(h) ~1 eV for holes and Φ_D(e) ~1.4 eV for electrons are expected. Contrary to our expectations, however, such barrier heights are in contrast with the experimental data of Fig. 1. We ascribe this discrepancy to a shift in the vacuum potential at the interface (Φ_D) towards the LUMO level of PCBM by ~0.64 eV, upon contact.¹⁹ Taking this shift into account the injection barrier for electrons is expected to decrease [Φ_D(e)−Φ_D=0.76 eV], while the barrier for holes to increase by an equal amount [Φ_D(h)+Φ_D=1.64 eV]. Although these predictions are based on the simplified energy level model of Fig. 2(b), they are qualitatively consistent with the experimental data of Figs. 1 and 2(a).

The transfer characteristics of a PCBM-based complementary-like inverter are shown in Fig. 3. The inset in Fig. 3(a) displays the schematic of the CMOS-like inverter circuit employed. The channel dimensions for both OFETs were identical and equal to L=10 μm, W=1000 μm. In the
In summary, we have demonstrated a complementary-like voltage inverter comprised of two identical ambipolar OFETs based on the solution processable methanofullerene PCBM. The inverter can function at room temperature exhibiting a maximum voltage gain of 18. This is one of the highest gains reported to date for OFET based inverters. Furthermore, the use of high mobility ambipolar organic semiconductors such as PCBM can be viewed as a significant step towards organic-based CMOS-like technology.

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